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## GAP WINDS OF THE STRAIT OF JUAN DE FUCA


By THOMAS R. REED

[Weather Bureau office, San Francisco, Calif., July 17, 1931]


The easterly gales at the west end of the Strait of Juan de Fuca constitute one of the notable climatic eccentricities of the North American Continent. Indeed it may not be extravagant to claim for them a position unique among the winds of the world. The writer knows nothing in meteorological literature which describes their counterpart, although winds of similar type though less violent are common to many other localities. The type (for it is believed these winds belong to a distinct type) undoubtedly reaches its culmination at or near Cape Flattery, Wash., at the entrance to the Strait of Juan de Fuca. This strait affords the principal sea-level egress for air evicted by gravity from the drainage basin of Puget and Washington Sounds. It lies in a nearly east-west direction and is about 75 miles long. At its western end it opens into the Pacific Ocean, and at its eastern end into Puget and Washington Sounds. It is walled on the north by the mountains of Vancouver Island and on the south by the Olympic Mountains. The basin into which the strait leads is flanked on the east by the Cascade Range and on the west by the Coast Range, including the Olympics.

Fortunately for the needs of investigation, the Weather Bureau is provided with ample observational data at this point, a fully equipped station having been maintained at Tatoosh Island, near the cape, for many years. The exposure of the wind instruments is good. They are located 113 feet above mean sea-level at a point where the island reaches a height of 80 feet above the sea. The island is described in Henry's "Climatology of the United States" as "a rock standing 75 to 100 feet above the ocean, three-fourths of a mile directly west of Cape Flattery, and at the mouth of the Strait of Juan de Fuca. With a rolling surface, it covers an area of a little less than 17 acres. The sides are precipitous. There are no trees or buildings that in any way interfere with the exposure of the instruments." The Weather Bureau installation is in the center of the island.

The frequency of easterly gales at Tatoosh Island is recognized by forecasters of the Weather Bureau, but it is doubtful if many of them have noted the individual and extraordinary character of these gales. Desiring to secure information in this regard, the writer appealed a few years ago to the Weather Bureau official at Tatoosh Island for a statement of the total number of easterly winds of 40 miles per hour or over which had been recorded there in the 5-year period, 1923–1927, inclusive. His answer stated that of 450 gales, all directions considered, which were recorded during that period, 219 were from an easterly quarter. Eleven of these gales were from the northeast, and three from the southeast. The remaining 205 were due east, an average of 1 in every 9 days for the 5-year period. When it is realized that the vast majority of these winds occurred during the winter season, the percentage of frequency for that time of year becomes more impressive still. The circumstance, however, which makes them especially worthy of note is not their frequency but their origin. They are not, properly speaking, gradient winds. That is to say, they do not approximate even remotely as a rule the air-flow requisite to balance the pressure gradient. Neither can they be classed as katabatic.

In support of the assertion that they are not gradient winds, considerable evidence has been adduced. Seventy-five cases have been considered. They include all easterly gales of 50 m. p. h., or over, which occurred during the inclusive period 1924–1927. Winds for 1923 were dropped out of the investigation because of the inadequacy of information touching the pressure situation at sea prior to 1924, information which could not be ignored in a discussion of coastal winds without casting doubt on the conclusions.

Also, it was decided to eliminate from consideration velocities of less than 50 m. p. h., since this economy of material would make the data more manageable without sacrificing any facts essential to correct deductions. Furthermore, it should be noted that all velocities are from records of the 4-cup anemometer; hence the adoption of 50 m. p. h. as the minimum to be considered really eliminates only winds of less than actual gale force, since the true velocity in miles per hour corresponding to 50 miles indicated on the 4-cup anemometer is 39.7 miles, or approximately the minimum that could be classed as a gale in Beaufort's terminology. It should be explained further that the 75 cases coming under this classification refer to the number of dates involved, not the number of individual gales; in several cases the gales extended over a period of two or more days, while in others they occurred on a single night both before and after midnight, thus requiring their entry as of two calendar days.

First let the statement that these winds are not ordinary pressure gradient phenomena be considered. While casual inspection of the synoptic charts for almost any of the dates involved would lead to this assumption, the writer sought to eliminate any grounds for contention by preparing a detailed table of pertinent data covering each instance. The table gave a full list of easterly gales at Tatoosh Island with dates of occurrence and set forth adjacent thereto maximum wind velocities and directions on concurrent dates at the four Weather Bureau stations nearest to Tatoosh, namely, Port Angeles situated on the strait about 63 miles eastsoutheast of Tatoosh; Seattle and Tacoma situated on the east side of

Puget Sound about 124 miles and 133 miles, respectively, southeast of Tatoosh; and North Head situated on a promontory of the coast 150 miles south of Tatoosh. Maximum winds recorded in the log of the Swiftsure Bank Lightship, anchored about 15 miles northwest of Tatoosh, also formed a part of the table.

No rigid inspection of the statistics was needed to convince one of the peculiar nature of Tatoosh winds, or to dissociate them from essentially pressure gradient phenomena. First were considered the maximum winds which occurred over Puget Sound on the dates when easterly gales were registered at Tatoosh. In only three cases did these winds reach gale force (40 m. p. h.) at Tacoma, and in only five at Seattle. Taking 50 miles as representing a gale for these stations, as was done for Tatoosh, the contrast was more striking yet. Only 1 such gale occurred at Tacoma and only 2 at Seattle, as against 75 at Tatoosh. None was recorded at Port Angeles. The mean velocity of the 75 maximum winds at Tatoosh was 60 m. p. h., at Tacoma 20 m. p. h., at Seattle 23 m. p. h., and at Port Angeles 16 m. p. h.

Significant as these comparisons are, they are rendered still more so when directions are considered. All the gales at Tatoosh were due east. If they were strictly gradient winds it would be natural to look for predominant easterly components in the winds occurring simultaneously over the region from which they were directly supplied, or which might be considered as their immediate source. This emphatically was not so. At Tacoma only 11 per cent of the maximum velocities had any easterly component whatever, at Seattle only 37 per cent, and at Port Angeles, where none might expect the greatest preponderance of due-east directions because of its location at the eastern end of the identical strait on which Tatoosh is situated, only 47 per cent showed an easterly component, while there were numerous cases of southwesterly directions and a few from the northwest. Of the two blows at Seattle which exceeded 50 m. p. h., the direction in one case was southwest and the other south. The one blow at Tacoma which exceeded 50 m. p. h. was from the southwest. On the same dates the maximum wind at Port Angeles was 24 m. p. h. southwest and 24 m. p. h. north, respectively.

These facts certainly disposed of any presumption that the Tatoosh gales are dependent on a general and marked pressure gradient over the immediate hinterland, if that term may be used to delimit the basin which incloses the waters of Puget and Washington Sounds. However, lest any doubt lurk on this point (the vagaries of surface wind movement over rugged country and landlocked waters being freely admitted) examination was made of the actual pressure gradient between the interior and the coast on the dates in question. The mean pressure difference at 5 p. m. between Seattle and Tatoosh, an air-line distance of about 124 miles, for the 75 days on which easterly gales occurred at the latter station, was 0.09 inch. This to be sure did not represent pressure differences computed for the exact moments at which extreme velocities were reached at Tatoosh. The labor involved in such research was too great to impose on the men employed in meteorological duties there and at Seattle. It did, nevertheless, furnish a serviceable approximation, the convincing nature of which was enhanced by considering individual cases. Thus, for example, three instances were found of no pressure difference between the two stations, and four where the gradient was negative; that is, *higher at Tatoosh than at Seattle*. While the wind had subsided to some extent in every case, and in two had undergone radical change in direction at 5 p. m. when the pressure observations were made, five of the seven instances were very remarkable, the wind continuing from an easterly quarter at Tatoosh at a velocity which ranged between 18 and 38 m. p. h. Here, indeed, is interesting material for the student of pressure-gradient phenomena.

The foregoing, while disposing of any assumption of an inland pressure gradient steep enough to account in itself for the easterly gales at Tatoosh, takes no cognizance of what may have been the pressure situation at sea at such times. The query naturally arises: Should we expect to find a pressure gradient offshore steep enough to account for the extraordinary gale phenomena at the cape? The answer is in the affirmative only if we consider the gales under discussion as belonging to a distinct type—an orographic or so-called bottle-neck type. An investigation was made of the barometric pressure over an extensive network of stations in the Pacific Northwest at the approximate time the gales listed were in progress. In most cases data secured from 5 p. m. (Pacific time) observations sufficed. In a few cases, however, 5 a. m. data were employed. Pressure data for numerous points at sea were obtained by interpolation from manuscript weather charts on file at the San Francisco office of the Weather Bureau, prepared from observations taken on shipboard a trifle earlier than at the land stations, viz, 4 a. m. or 4 p. m., Pacific time.

A cursory examination of these data confirmed the natural expectation of finding conditions best for an easterly gale at Tatoosh when the pressure is abnormally high to the northeast and low to the southwest. Closer inspection, however, revealed the inadequacy of pressure gradients therein to account per se for the velocities which actually occurred, even in the relatively few instances which called for winds of gale force over the open sea. That the pressure situation both on land and at sea contributed indirectly to the gales at Tatoosh is not questioned; that it did so in such a way as to entitle them to classification as gradient winds is denied.

In support of this denial there is additional testimony. A composite isobaric chart was constructed, presenting means of the pressure data referred to above. This chart, while confirming the observation that high pressure to the northeast and low pressure to the southwest of Tatoosh are the ideal conditions for easterly blows at that point, also demonstrated by the very weakness of the composite gradient the fact that such blows may occur under the most diverse individual conditions of pressure distribution. In other words, it appeared that easterly gales may occur at Tatoosh with the lowest pressure in any of the three sectors, north, south, or west. There were 35 dates when the lowest pressure was to the southwest of Tatoosh, 27 when the lowest pressure was to the northwest, 8 when it was lowest at Eureka, Calif., and 1 when it was lowest at Kamloops, British Columbia. The preparation of charts more closely synchronized with the time of occurrence of the peak winds might change these figures somewhat; nevertheless it is believed the ratios would remain substantially the same.

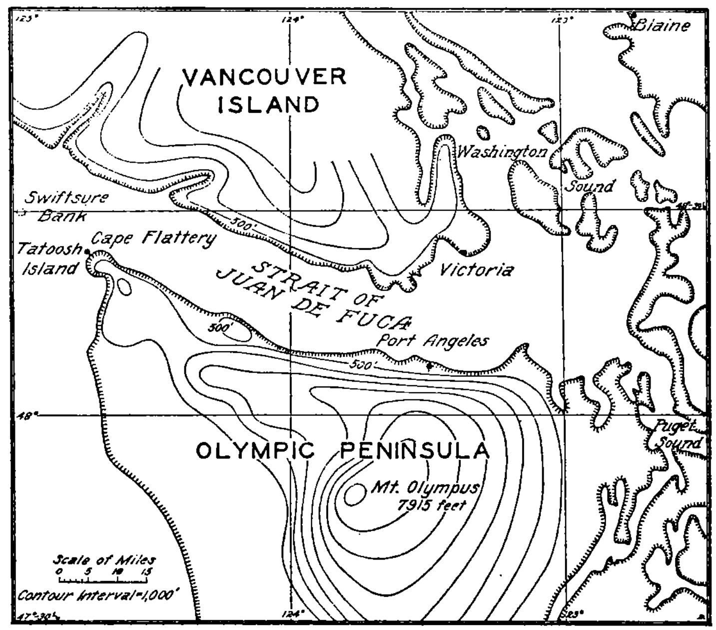
Comparison of winds at the two nearest coastal observation points was made: At Estevan, located on the southwest side of Vancouver Island 110 miles northwest of Tatoosh, and at North Head, situated on the Washington coast 150 miles south of Tatoosh. Maximum wind data were not obtainable for Estevan, but current wind data reported at the time of the regular 5 a. m. and 5 p. m. observations were compiled from entries on the pencil charts at San Francisco. These showed 14 instances of a calm at Estevan when the wind was blowing out of the strait at Tatoosh Island at a rate of anywhere from 18 to 76 miles per hour. In only 3 out of 14 cases was the velocity at Tatoosh less than 40 m. p. h. Significant, too, was the great variety of directions recorded at Estevan at other times. In the 71 cases investigated (Estevan reports were missing on 4 dates) all but 6 showed due east winds at Tatoosh, and an average velocity for all of 38 m. p. h. Simultaneously, Estevan showed, in addition to the 14 calms mentioned, numerous cases of winds from the north, northwest, and west, with a mean velocity of 8 m. p. h.

Passing from the coast nortwest of Tatoosh to that lying south of it, wind figures for North Head were examined. Here maximum velocities were available. North Head offers the best exposure for the registration of gradient winds of any of the stations for which data are submitted, as it is situated on a promontory of the southern Washington coast 250 feet above the sea. Moreover, this station lies in the same climatic zone as Tatoosh and storms that affect one usually affect both. It is recognized that orographic influences tend to accentuate the velocity of the wind at North Head, and that many more gales are recorded there than would be found in that vicinity at sea. This is not only a logical inference, but one frequently confirmed by radiographic weather reports from ships in the offing. Nevertheless North Head offers as good an exposure for the registration of gradient winds, both direction and velocity considered, as could be found in that section of the coast. It is especially valuable in connection with this study, as storms that produce southerly gales at Tatoosh are almost certain to produce as high or higher velocities at North Head. The percentage of gale frequency is the same for both. During the period 1923–1927 inclusive there were 450 gales of all directions at Tatoosh and 440 at North Head. Gales at North Head as a rule are obviously related to the pressure gradient at sea, while a substantial percentage of those at Tatoosh are not. Of the 75 dates on which easterly gales of 50 m. p. h. or over were recorded at Tatoosh, the maximum wind at North Head was from the east on only 32, with a mean velocity for the 32 occasions of 27 m. p. h. The direction on most of the other dates was from the south. The mean velocity at North Head for all directions was 39 m. p. h.

A survey of the foregoing evidence, while disposing of the inference that the Tatoosh gales are pressure gradient phenomena in the strict sense of that term, leaves untouched the question of their relation to the horizontal temperature gradient. Can they be classed as katabatic? Almost as many easterly gales were recorded at Tatoosh with the temperature above normal over Puget Sound as with the temperature below normal. Nor does it appear absolutely necessary to have the air in the interior colder than at sea, as witness the blows of June 25, 1925, and September 18, 1927. On the latter date the highest temperature of record for that time of year, 76°, occurred at Tatoosh, and even higher temperatures were recorded in the interior; while on the former date still more extreme conditions prevailed, the highest temperatures ever recorded there being reached at both Seattle and Tacoma.

The vagaries of wind direction and velocity introduced by irregularities in the terrain are admitted. It may be suggested therefore, that easterly gales at Tatoosh are frequently of a quite local character and do not reflect wind conditions even a few miles out in the channel. The records of the Swiftsure Bank Lightship were studied and gave a strong indorsement to the reliability of Tatoosh data as representing the general wind movement out of the strait. These records, though not obtained by instrumental means, are believed to represent very conservative estimates. In the opinion of the lightship master they are much more likely to be underestimates than overestimates of wind force. Moreover, they actually represent only the highest force noted at observations taken at two hour intervals, i. e., at 2, 4, 6, 8, etc., o'clock. Velocities between times may have been higher although allowed to pass without note. With this in mind it was recognized that the wind movement near the middle entrance of the strait where the lightship is anchored, fully 15 miles northwest of Tatoosh, agreed remarkably well with the easterly gale data for Tatoosh itself. There were 42 days when the force (Beaufort scale) exceeded 7, and the average force for the 75 cases was between 7 and 8. The winds, therefore, are not a vagary peculiar to the sides of the strait, but obtain in mid-channel as well.

In seeking to account for this phenomenon, obviously we must look elsewhere than to a marked pressure or temperature gradient for the explanation. That the




winds are fundamentally due to difference in air pressure between the interior regions and the sea is evident, although this difference may not be expressed as a pressure gradient in the vicinity of Tatoosh or the Strait of Juan de Fuca. Admitting that the pressure difference exists, however, as between the air mass over the interior and that at sea, the peculiar manner of outflow arising from such difference rather that the amount of the difference must account very largely for the extraordinary rate of movement of the air at and near the point of ejection. It must be peculiarly an orographic phenomenon, originating in a pressure inequality and varying as the degree of such inequality, but deriving its remarkable velocity from the converging sides of the channel through which it makes its way.

The physiographical conditions for the production of such winds at Tatoosh are ideal. The drainage basin which includes Puget and Washington Sounds furnishes the reservoir for a vast body of air of nearly homogeneous density. The converging terrestrial walls flanking the Strait of Juan de Fuca constitute the funnel through which the bulk of this air must flow at the behest of lower pressure at sea. The contracting channel acting like a Venturi tube increases the speed of the flow until by the time the gap at the point of ejection is reached extraordinary velocities are attained.

Winds similar in type if not in strength are to be found wherever the character of the terrain restricts to some gap or gorge the passage of air from regions of higher to regions of lower pressure. They are a common orographic phenomenon of the moving air. For this reason some special term to define and describe them seems to be demanded. Maj. E. H. Bowie has suggested the name "bottleneck winds." "Funnel winds" was used some years ago by Mr. S. L. Trotter in a paper dealing with marked incongruities in gale velocities at certain observation points on the Atlantic coast.[1] The writer has already employed the term "orographic" in referring to such winds, although in the opinion of some it is open to objection as being too general. "Gap winds" is sufficiently specific and is favored by at least one meteorologist of eminence.[2] "Orographic" would, it is true, apply to a wider variety of winds than any of the other terms suggested. It would describe winds which increase in velocity by passing *over* a mountain barrier equally as well as those which increase in velocity by passing *through* a gap or gorge. Both phenomena deserve appropriate nomenclature. They are so characteristic of the moving air as to have become a commonplace of airway weather observations in mountain districts. They occur in such regions with a consistency which would be surprising if the cause were less obvious. Orographic winds, whether of the gorge, gap, or ridge variety, are obeying in principle if not in detail the law exhibited in the functioning of a wind tunnel or a Venturi tube. In the gorge, three sides of a Venturi are roughly represented; in the ridge but one. But the constriction affecting the flow operates effectively, though in varying degree, in all cases. Indeed the term "Venturi winds" may be offered without doing violence to logic.

[1] Local Peculiarities of Wind Velocity and Movement Atlantic Seaboard—Eastport, Me., to Jacksonville, Fla., by Spencer Lee Trotter. Page 634, vol. 48, Monthly Weather Review.

[2] In a marginal comment on the author's manuscript, Prof. W. J. Humphreys wrote: "Orographic winds is not good—it is too general. Why not 'Gap winds?' That is what they are. I have a vague impression that this term has been used."

# SOME EFFECTS OF CALIFORNIA MOUNTAIN BARRIERS ON UPPER AIR WINDS AND SEA-LEVEL ISOBARS

By DELBERT M. LITTLE

[Weather Bureau Airport Station, Okland, Calif., August 17, 1931]

The intensive weather service for airways, with its numerous hourly and three-hourly reports and six-hourly upper-air data, has provided an opportunity for meteorologists to examine in great detail the day to day meteorological situations. Accurate barometer readings and upper-air wind data are most important to a proper understanding of the situations portrayed by synoptic charts. Mountain barriers play an important though invisible part on the weather charts, and it therefore seems proper that some effects of these barriers on barometric pressure and winds, as deduced from the California 3-hourly airways weather charts, be presented.

Upper-air wind data for California are obtained from the following 11 pilot balloon stations, each in or near the State: Redding, Oakland, Fresno, Lebec, Los Angeles, San Diego, March Field (Riverside), Santa Maria, Reno, Nev., Yuma, Ariz., and Medford, Oreg. Of these, 7 are Weather Bureau stations, 2 Signal Corps stations, 1 a Navy station, and 1 privately maintained but cooperating with the Weather Bureau.

Of the California 3-hourly reporting stations, 15 use the mercurial barometer and are located in or just beyond the State at the following places: Eureka, Redding, Oakland, San Jose, Fresno, Bakersfield, Lebec, Estero, Los Angeles, San Diego, March Field (Riverside), Tonopah, Nev., Reno, Nev., Phoenix, Ariz., and Medford, Oreg. Reports also are received from a number of stations to the east and north of the last four named. In addition, there are 30 stations in California reporting pressure from aneroid barometers. Readings from aneroid barometers at first were of little value, (*a*) because of their uncertain height above sea level and (*b*) because of slowly changing instrumental errors. Eventually a plan was worked out to establish arbitrary corrections, to be revised from time to time, for reduction to sea level of all readings from aneroid barometers at low-elevation stations, i. e., stations less than 400 feet above sea level. Each arbitrary correction was based upon the departure of the aneroid reading from an interpolated value secured from the regular 8 a. m. and 8 p. m. seventy-fifth meridian time charts at times when "flat" pressure maps are evident and *no strong upper air winds prevailed.*

For each aneroid barometer at a high elevation a reduction table was secured from a Weather Bureau station whose elevation was approximately the same as the aneroid to be reduced. Then a small arbitrary correction was determined by the method of interpolation described above in order to fit the aneroid reading very closely to the reduction table. Arbitrary corrections are changed by a new interpolated value from time to time, thus very nearly eliminating any error due to seasonal march of temperature or changed instrumental error. It is safe to say that ordinarily the accuracy of these aneroid reductions is to within 0.03 inch of the true sea-level pressure values. With one-third of the barometers of the mercurial type well distributed over the State, it is not at all difficult to detect errors in and adjust readings of the aneroids at other stations in the network.

Approximately 50 airway and off-airway reports are entered every three hours on a base map printed from a plate of the Stanford relief model of California. The valleys and mountain ranges stand out in striking contrast to aid the meteorologist in determining the effect of the terrain on weather, as well as to visually aid pilots seeking advice as to the weather over the airway. Some of the salient facts noted on the synoptic maps are as follows:

1. Exceptionally steep pressure gradients at times prevail over mountain barriers and the isobars very frequently follow the mountains in a general way, but not exactly parallel to elevation contours.

2. In cases of extreme pressure gradients, the upper air winds immediately over the barriers are of strong to hurricane force and at nearly *right angles* to the sea-level isobars along the mountains.

3. The surface barometric pressure is increased on the windward side and decreased on the leeward side of mountain barriers in comparison with pressures reported at considerable distances from the mountains.